Observed recent trends in tropical cyclone rainfall over the North Atlantic and the North Pacific

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[1] In this study, we use Tropical Rainfall Measurement Mission and Global Precipitation Climatology Project rainfall data together with historical storm track records to examine the trend of tropical cyclone (TC) rainfall in the North Atlantic and the northeast and northwest Pacific during two recent decades (1988–1997 and 1998–2007). We find that there is an approximate linear relationship between TC rain (defined as accumulated total rainfall along storm tracks) and storm intensity as classified by the Saffir-Simpson scheme. During the data period, total TC rain has trended upward at a rate of 23.8% ± 23.5% per decade over the North Atlantic but downward with a rate of 25.1% ± 19.7% per decade over the northeast Pacific. Over the northwest Pacific, there is a reduction in TC rain of approximately 20.9% ± 13.5% per decade, possibly associated with a strong interdecadal-scale oscillation. Storm characteristics such as duration and TC rain energy per storm (EPS) remain unchanged for the North Atlantic and the northeast Pacific. For the northwest Pacific, a 28% ± 18% reduction in EPS from the first decade (1988–1997) to the second decade (1998–2007) is found with the track data from the Joint Typhoon Warning Center. Analyses of the probability distribution function of TC rain show that there is an overall increase in TC frequency across the entire TC rainfall spectrum over the North Atlantic but an overall decrease for the northeast Pacific. In the northwest Pacific, we find a redistribution in EPS with decreased frequency in heavy-rain storms and increased frequency in light-rain storms. Overall, trends in TC rain in the different ocean basins are consistent with long-term relative changes in the ambient large-scale sea surface temperature and vertical wind shear and, to a lesser extent, tropical cyclone Maximum Potential Intensity.

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1. Introduction

[2] Tropical cyclones (TC) are among nature's most destructive forces. Whether the number and the intensity of TCs have changed or will change in a warming climate has been the subject of many studies [*Goldenberg et al.*, 2001; *Webster et al.*, 2005; *Chan*, 2006; *Landsea et al.*, 2006; *Klotzbach*, 2006; *Kossin et al.*, 2007]. However, the issue is far from settled, due to large interannual and interdecadal variability in the frequency and intensity of TCs and limitation in the availability and quality of global long-term historical records of TCs [*Pielke et al.*, 2005; *Shepherd and Knutson*, 2007; *Landsea et al.*, 2006, 2008; *Knutson et al.*, 2010]. Despite large uncertainties in observed long-term TC frequency and intensity change, numerical models have predicted that TC-related rainfall rates are likely to increase with greenhouse warming [*Knutson and Tuleya*, 2004; *Bengtsson et al.*, 2007]. Such models have projected increase in storm-centered rain rates in the late 21st century in the range of 3%–37%, stemming from increased evaporation from the warmer oceans and increased moisture in the atmosphere. These model results suggest that through moisture convergence feedback, increased available moisture in the atmosphere is expected to lead to greater TC rain rates.

[3] Previous studies from precipitation gauge data found that the frequency of extreme rainfall over some land areas has increased in the last several decades [*Karl and Knight*, 1998; *Groisman et al.*, 2004], as well as over the tropical oceans based on long-term satellite precipitation data [*Lau and Wu*, 2007]. In the coastal regions of South China and southeastern United States, TCs account for a significant portion of total rainfall, and even more so for extreme rainfall, and an increase in major TCs may be related to extreme rain events [*Wu et al.*, 2007; *Shepherd et al.*, 2007]. *Lau et al.* [2008] recently studied the relationship between TC-related rainfall and extreme rain events in North Atlantic

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and northwest Pacific using nearly 30 years of Global Precipitation Climatology Project (GPCP) pentad data. They found that TCs contribute to increasing amount of extreme rain events in the two ocean basins, with more pronounced signal in the North Atlantic Ocean than the northwest Pacific, in part due to the larger increase in warm pool size in the former. Despite well-founded theoretical expectation and modeling projections, long-term (> decades) trends in observed TC-related rainfall rates over major ocean basins have not been documented [*Knutson et al.*, 2010].

[4] In this study, possible long-term trends in TC-related rainfall measurements are examined for three major ocean basins, that is, the North Atlantic, the northeast Pacific and the northwest Pacific, using GPCP data and historical storm track data. Section 2 describes the data and methodology. Section 3 examines the relationship between TC rain and TC intensity from GPCP pentad data and the more recent high-resolution Tropical Rainfall Measurement Mission (TRMM) data. Section 4 shows results of long-term trend analysis in TC rain. Section 5 examines trends in the large-scale environment that may be responsible for the observed changes in TC rainfall. Section 6 summarizes the results.

2. Data and Methodology

[5] The primary precipitation data used in this study is the pentad (5 day mean) satellite rainfall measurements from GPCP. The GPCP rainfall is a merged product that combines available surface rain gauge and operational satellite rainfall estimates to provide a state-of-the-art, multidecadal (1979–2010) global data for climate studies [*Adler et al.*, 2003; *Xie et al.*, 2003]. For cross validation, daily rainfall derived from 3-hourly TRMM Multisatellite Precipitation Analysis (TMPA) data for 1998–2007 [*Huffman et al.*, 2007] is used to compare with GPCP. The 6-hourly best storm track data for the North Atlantic and northeast Pacific are from the National Hurricane Center [*Jarvinen et al.*, 1984]. For the northwest Pacific, we use storm track data from the Joint Typhoon Warning Center (JTWC) [*Chu et al.*, 2002], with a correction of wind speed [*Emanuel*, 2005]. For cross-checking, storm track data from the International Best Track Archive for Climate Stewardship (IBTrACS) [*Knapp et al.*, 2010] from three other sources, the Chinese Meteorological Administration Shanghai Typhoon Institute, the Hong Kong Observatory, and the Regional Specialized Meteorological Center (RSMC) at Tokyo, are also used. Data for sea surface temperature (HadISST1) are from the Hadley Center [*Rayner et al.*, 2003]. The NCEP-NCAR Reanalysis-1 [*Kalnay et al.*, 1996] surface air temperature, vertical temperature, humidity and wind profiles are used to compute changes in TC-related large-scale environmental factors such as vertical wind shear and TC Maximum Potential Index (MPI). The spatial resolution is 2.5° latitude × 2.5° longitude for GPCP and NCAR-NCEP Reanalysis, 0.25° × 0.25° for TRMM, and 1° × 1° for SST. A TC rain data consisting of total accumulated rainfall associated with each TC is constructed for three ocean basins (see discussion in next paragraph). However, in our preliminary analysis, we find systematic bias that may affect the trends in the constructed TC rain data between the pre-SSMI (1979–1987) and the post-SSMI period (1988–2007), possibly due to inclusion of the SSMI data in the rainfall retrieval algorithm [*Zhou and Lau*, 2010]. Hence, only results for the post-SSMI period are reported here.

[6] For this study, we use a Lagrangian approach (following each storm track) to estimate the total accumulated rainfall for each storm over its lifetime (hereafter denoted as TC rain) using the 6-hourly storm track data. We define TC rain as the accumulated amount that falls within an area of 500 km radius, from the center of the TC within the same day (for TRMM data) and the same pentad (for the GPCP pentad data) along the entire track [*Larson et al.* 2005; *Rodgers et al.* 2000, 2001]. The TC accumulated rainfall is obtained for each storm for the North Atlantic, the northwest Pacific and the northeast Pacific, respectively. We stress at the outset that because of the large spatial and temporal averaging in the GPCP pentad data, and the constant radius of influence assumed for all TCs, the TC rain products developed here are not intended to estimate instantaneous or maximum rain rates but rather as an integral measure of total rain energy associated with a TC. We recognize that actual measures of rain rates are more desirable in order to estimate storm intensity, and to compare with climate model results. However, determining realistic trends of TC rain rates will require long-term (multidecadal), high temporal (3-hourly or at least daily) and spatial resolution (25 km or less) rainfall data, which currently do not exist. Hence our effort here is aimed at exploring an alternate, albeit admittedly crude, measure of TC rainfall in terms of accumulated total rain and mean rain rate for climate change studies, using available global rainfall data. For estimating long-term trends, the large spatial and temporal averaging used for our TC rain estimate may help to reduce the inherent noise in high-frequency rainfall data, and produce more stable climate scale statistics. Besides the lack of resolution to produce accurate TC rain rates, another shortcoming of the TC rain data is the possible aliasing of non-TC rain arising from (1) the use of a rather large (500 km) constant radius of influence and (2) the use of the rainfall in the entire pentad along the storm track. Since latent heat is released by rainfall, TC rain can be more meaningfully identified as the total energy generated by a given TC. To facilitate the comparison with other forms of energy, hereafter, we convert the TC rain amount to the unit of Energy Year (EY = 5.10×10^{20} Joule), which is the estimated world primary energy consumption in 2007 (http://eia.gov/aer/txt/ptb1103.html).

3. GPCP and TRMM TC Rain Comparison

[7] Figure 1 shows scatterplot of TC rain estimated from GPCP and TRMM data for different TC categories according to the Saffir-Simpson classification for the three ocean basins. The two TC rain data are highly correlated (correlation coefficients in the range of 0.90–0.98), but the GPCP estimates are systematically higher than that of TRMM by 30–40 percent for all storm categories. This is likely due to the coarse spatial and temporal resolutions of the GPCP data and possibly the aliasing of non-TC rain. However, within GPCP there are no systematic differences among TC categories, or among the three ocean basins (not shown). Therefore it is reasonable to assume that despite its coarse resolution, the GPCP estimates of TC rain would be

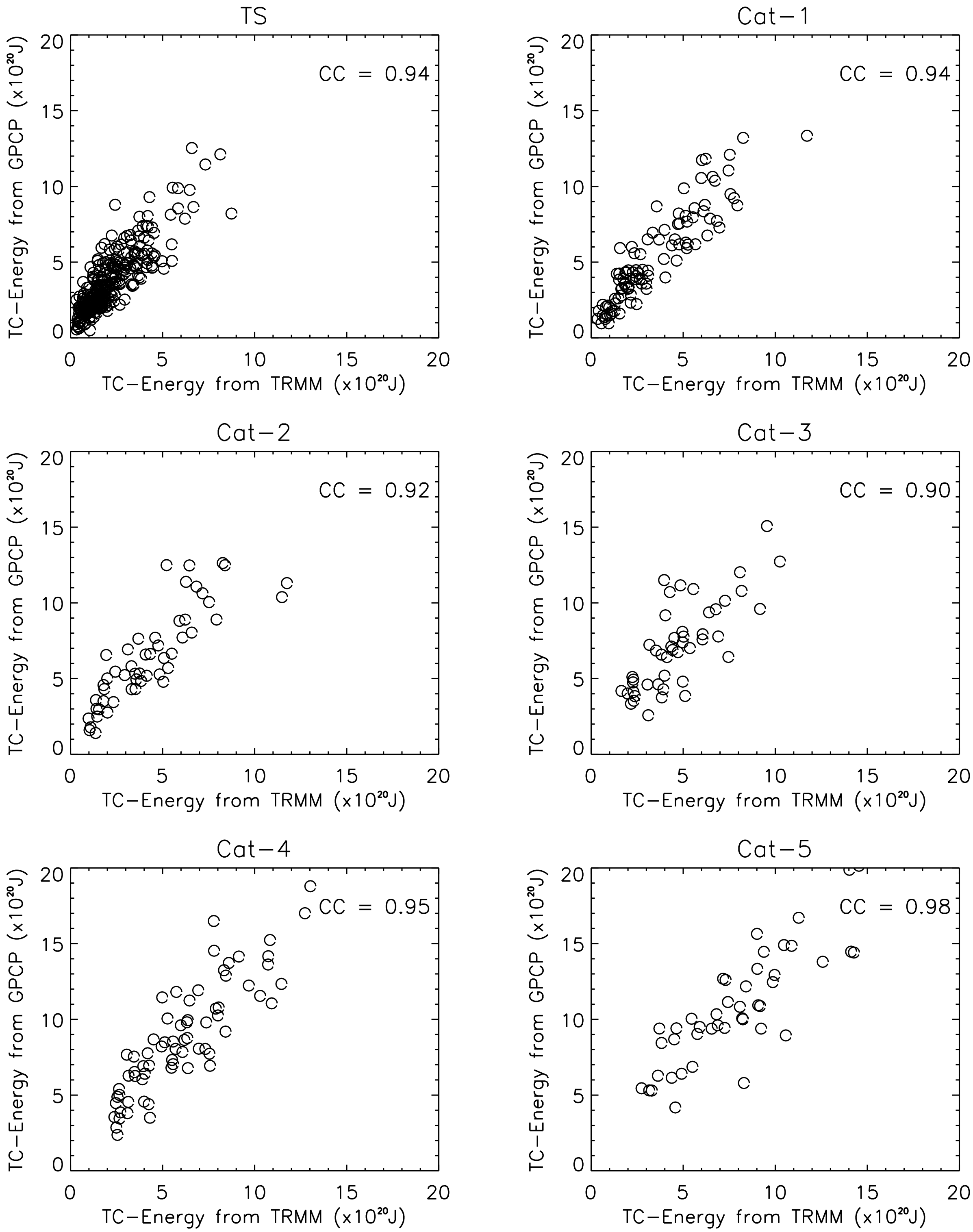

Figure 1. Scattered plots of TC rain in energy units from TRMM versus from GPCP for different TC categories during the overlapping period (1998–2007) of the two data sets.

self-consistentfor different storm categories and can be used over different ocean basins.

[8] Numerical simulations have suggested that TC rainfall rates and storm intensity increase as the climate warms [*Knutson and Tuleya*, 2004]. However, the relationship between TC intensity and TC rain has not been well established. A number of studies [*Shepherd et al.*, 2007; *Jiang and Zipser*, 2010] have examined the relationship between TC rainfall and intensity. For example, the radial distribution of azimuthally averaged instantaneous rain rates from storm center shows a high correlation with storm intensity [*Lonfat et al.*, 2004], but are strongly modulated by

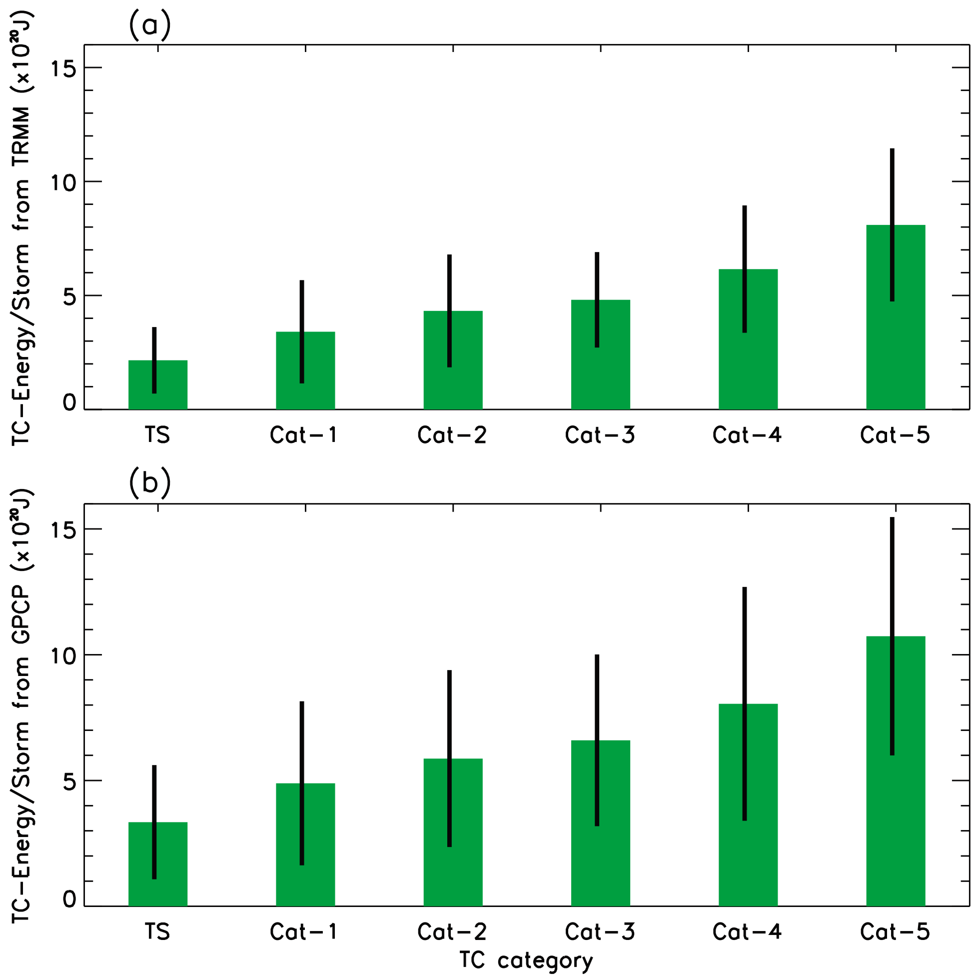

Figure 2. Mean (green bar) and standard deviation (black line) of TC rain per storm in energy units for different TC categories from (a) TRMM and (b) GPCP.

vertical wind shear, total precipitable water, horizontal moisture convergence, ocean surface flux and topography [*Lonfat et al.*, 2007; *Jiang et al.*, 2008]. Moreover, TC rain amount over the lifetime of a storm, defined as TC rain, depends on multiple factors governing storm intensity and duration. We are not aware of any study that has examined the relationship between storm intensity and TC rain over the entire TC life cycle.

[9] Figure 2 shows the mean and standard deviation of TC energy (TC rain in units of energy) per storm (defined as EPS) versus the Saffir-Simpson storm category based on GPCP and TRMM data. Notably, TC energy increases almost linearly with storm intensity, with TS and Category 1, 2 storms on average generating less than 2–5 $\times$ 10^{20} Joule of energy (0.5$\sim$1.0 EY) per storm, while Category 3, 4 and 5, produce 5–7 $\times$ 10^{20} Joule (1.0$\sim$1.5 EY) per storm (Figure 2a). The more concurrent relationship between daily mean storm wind (averaged from four measurements per day) and daily storm rain also shows positive correlation (not shown), as reported by [*Lonfat et al.*, 2004; *Jiang et al.*, 2008]. Large standard deviations are expected due to many other factors affecting TC rain [*Lonfat et al.*, 2007; *Jiang et al.*, 2008]. The mean TC rain from GPCP is larger than that from TRMM (Figure 2b) for the same reasons discussed before. The above results demonstrate that GPCP and TRMM TC rain data have similar properties with respect to TC intensity for the overlapping period and for all rainfall categories, providing some reassurance that GPCP TC rain can be used for studies of the longer data period (1988–2007).

4. Recent Trends in TC Rain

[10] In this work, the term "trend" is defined by the linear regression or differences in statistics between decades within the data record. As such, a trend signal referred to here may be influenced by and/or a part of natural interdecadal-scale oscillation not resolved by the length of the data record. In the following discussions, the term "significant" is used, to mean "statistically significant exceeding the 90% confidence level (c.l.)." However, due to the relatively short data records, this does not necessarily mean the trend is highly unusual in terms of its significance compared to natural multidecadal variability. Figure 3 shows the time series and estimated trends of total number of TC and TC energy from 1988 to 2007 for the North Atlantic, the northeast Pacific and the northwest Pacific, respectively. It can be seen that both TC rain and TC number have large interannual and interdecadal-scale variations. Over the North Atlantic, a

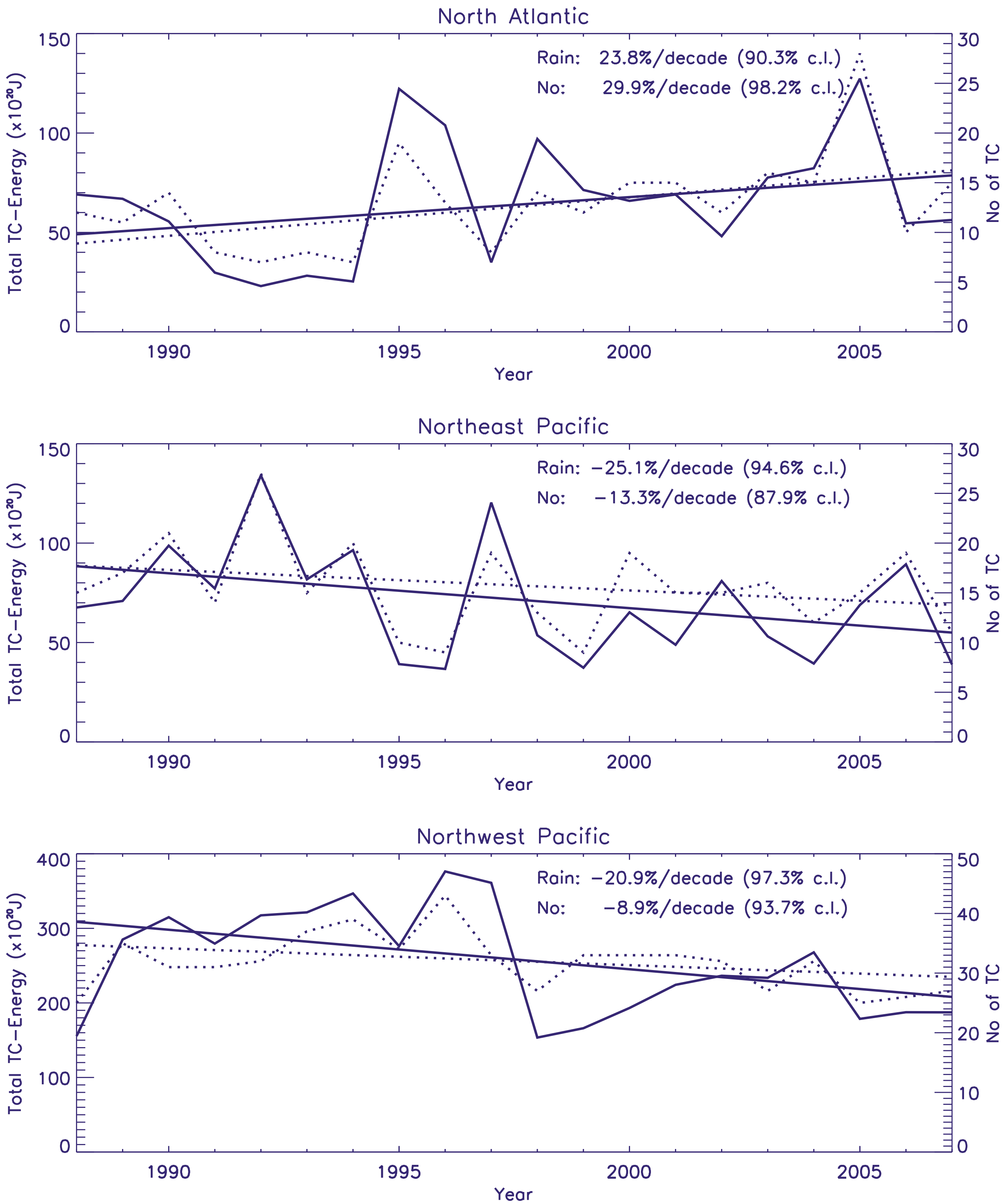

Figure 3. Time series and the linear regression fit of total TC rain in energy units (solid line) and TC number (dotted line) for the North Atlantic, the northeast Pacific, and the northwest Pacific regions. The trends shown by the percentage change per decade are derived from the slopes of linear regression. Statistical confidence level (c.l.) is estimated based on Student's *t* test.

significant increase of 23.8% ± 23.5% per decade in TC rain and 29.9% ± 17.6% in TC number is found. In contrast, over the northeast Pacific, moderate negative trends of 25.1% ± 19.7% per decade in TC rain and 13.3% ± 14.6% in TC number can be detected. Over the northwest Pacific, reductions of 20.9% ± 13.5% per decade in TC rain, and 8.9% ± 7.4% in TC number are found. Here, the negative trends are apparently associated with a large drop in TC activities beginning in the 1998 and lasting through the 2000s, possibly related to an interdecadal-scale oscillation [*Chan and Liu*, 2004].

[11] To further examine the trend of TC rain in each basin, we divide the TCs into three groups, TS, Cat 1–3, Cat 4–5, identified as weak, intermediate and intense storms, respectively, and an All-TC category to include all storms. To focus on the long-term (>decadal) changes, we compute the TC number, TC rain, TC duration, energy per storm (EPS) and related statistics separately for two equal halves of 10 years each, that is, 1988–1997 and 1998–2007, and compare the statistics between the two halves. For the northwest Pacific, where alternate definitions of storm tracks and TC classification used by different operational centers exist, we also conduct similar analysis using storm tracks from other sources to assess the uncertainties (see auxiliary material).[1]

[12] Over the North Atlantic, there is a general increase in TC number in all storm categories (Figure 4a). However, significant increase in TC number is found only in TS (+45%), Cat 4–5 (+108%), and All-TC (+42%). In contrast, over the northeast Pacific, there is a general decrease in all categories except in TS, with significant reduction (−56%) only in Cat 4–5. For the northwest Pacific, TC number remains statistically unchanged in TS and Cat 4–5, even though there is a significant reduction (−13%) in All-TC and in Cat 1–3 (−26%). The TC rain trends (Figures 4d–4f) show similar overall characteristics, but somewhat stronger signals in decreasing trends. For the North Atlantic, TC rain increases for all categories, with significant increase in TS (37%), and in All-TC (34%). The northeast Pacific shows significant reduction in TC rain in Cat 1–3 (−27%), and Cat 4–5 (−57%), with a 30% overall reduction of All-TC rain. For the northwest Pacific, significant reductions are found in all TC rain categories, with −30%, −43% −24%, and −33% for TS, Cat 1–3, Cat 4–5, and All-TC, respectively. Results comparing storm track data from three other sources (Shanghai Typhoon Institute, RSMC at Kokyo and Hong Kong Observatory) for the northwest Pacific with that from JTWC indicate that there is an overall consistency in the decreasing trends in TC number and TC rain in all categories with various levels of statistical significance, regardless of the large differences in the storm intensities among different data sources. All data sources show a highly significant reduction (>98% c.l.) of total TC number in the order of 14%–20% range and an overall significant reduction of total TC rain in the order of 16%–30% (>98% c.l.) with the strongest signal coming from JTWC data (see auxiliary material). The increase in TC number and TC rain in the North Atlantic and the corresponding decrease in the northeast Pacific is consistent with previous studies [*Wang and Lee*, 2009, 2010]. These authors suggested that inverse variations of TC activities in these two ocean basins on both interannual and multidecadal time scales are due to opposite changes of atmosphere instability and vertical wind shear associated with the Atlantic Multidecadal Oscillations.

[13] For storm characteristics, we have computed and compared the averaged duration per storm and the energy per storm (EPS). Figures 5a–5c show that for all three basins, the more intense storms generally have longer lifetimes, with 10 or more days for Cat 4–5, approximately doubling those for TS. However, we find no significant change in storm duration for all storm categories in the North Atlantic, a modest reduction in All-TC duration in the northeast Pacific, but significant reduction in duration per storm in the northwest Pacific in all categories (Figure 5c). In the northwest Pacific, we note a significant reduction in duration of 28% ± 18% for All-TC. This corresponds to a shortening of the storm life from about 10 days to 7 days. A reduction in storm duration could mean faster moving storms and less time spent over the open ocean. Consequently, there will be less transfer of latent heat from ocean to the TC, resulting in less energy per storm (EPS), as shown in Figure 5f for the northwest Pacific. This is also consistent with the results shown in the TC rain probability distribution function analyses (see discussions below). However, no significant changes in EPS for northwest Pacific storms are found using storm track data from other sources (not shown). Hence, this result must be taken with extreme caution.

[14] Another quantity desirable for comparison between observation and climate model simulation is the maximum instantaneous rain rate associated with TC. However, the computation of this quantity is limited by the coarse spatial and temporal resolutions of the GPCP pentad data. In an effort to gain some crude insight, we have examined the mean intensity (defined as total rain amount divided by total storm days) and compared the statistics of the two periods. However, we find no significant trends in the North Atlantic and the northeast Pacific (not shown). In the northwest Pacific, there are small significant increasing trends in the mean rain intensity in TS and Cat 4–5 using the JTWC track data, but no significant trends are found using the three other track data.

[15] The systematic change in storm characteristics during the two periods is further illustrated by examining the difference in the mean probability distribution functions (PDFs) of EPS from the first to second period (Figure 6). The rainfall-based categorization of TC energy has an advantage over storm intensity classification by the Saffir-Simpson scheme, in that a unified definition of storm strength (as measured by total rain energy), independent of exact procedures used by different operational centers, can be used for all ocean basins. To facilitate discussion, also shown in Figure 7 are the climatological thresholds of the top 10% (T10), and the median (T50) EPS in units of EY. It is noteworthy that climatologically the northwest Pacific has the most energetic (wettest) storms, with much higher EPS thresholds for T10 and T50 (2.8 EY, 1.4 EY) compared to corresponding thresholds (2.0 EY, 0.79 EY) for the North Atlantic, and (1.5 EY, 0.78 EY) for the northeast Pacific. The lowest T10 EPS threshold in the northeast Pacific also suggests that the TCs there are the least energetic of the three basins. Over the North Atlantic, the PDF difference suggests an overall

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011JD016510.

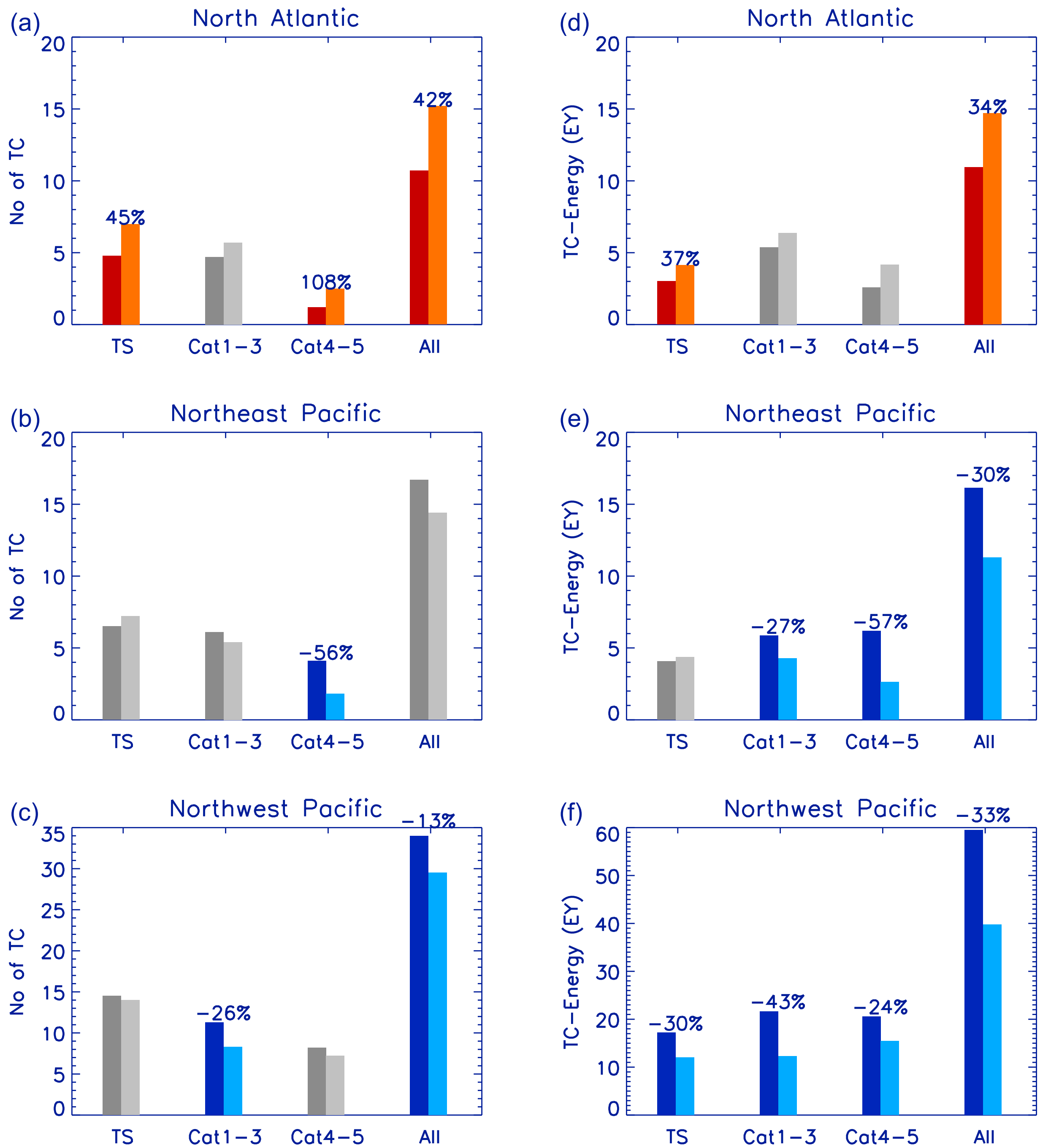

Figure 4. Comparisons of (a–c) annual mean number of TCs and (d–f) basin total TC energy from three TC groups and all TCs for the first 10 years (1988–1997, darker bars) and second 10 years (1998–2007, lighter bars) in each ocean basin. Orange bars indicate significant (above 90% c.l.) positive changes, and blue bars indicate significant (above 90% c.l.) negative changes. Numerical values are shown only for significant percentage changes.

increase in TC frequency of up to 50% across almost the entire rainfall spectrum. On the other hand, the northeast Pacific shows almost the opposite pattern with an overall reduction in frequency for all moderately and strongly energetic storms (EPS > T50), having the largest reduction (up to 100%) for the very energetic storms (EPS > T10). In the northwest Pacific, there appears to be an internal redistribution of the PDF, with increased number of TCs for less energetic storms (EPS < T50) and reduced number of TCs for more energetic storms (EPS > T50). Here, the reduction in the most energetic storms (EPS > T10) is found to be greater than 50%. Since more energetic storms tend to have longer duration, the shift in TC energy PDF in the northwest Pacific is in agreement with the reduction in overall duration of storms in the region noted previously. In addition, the shift and internal redistribution of

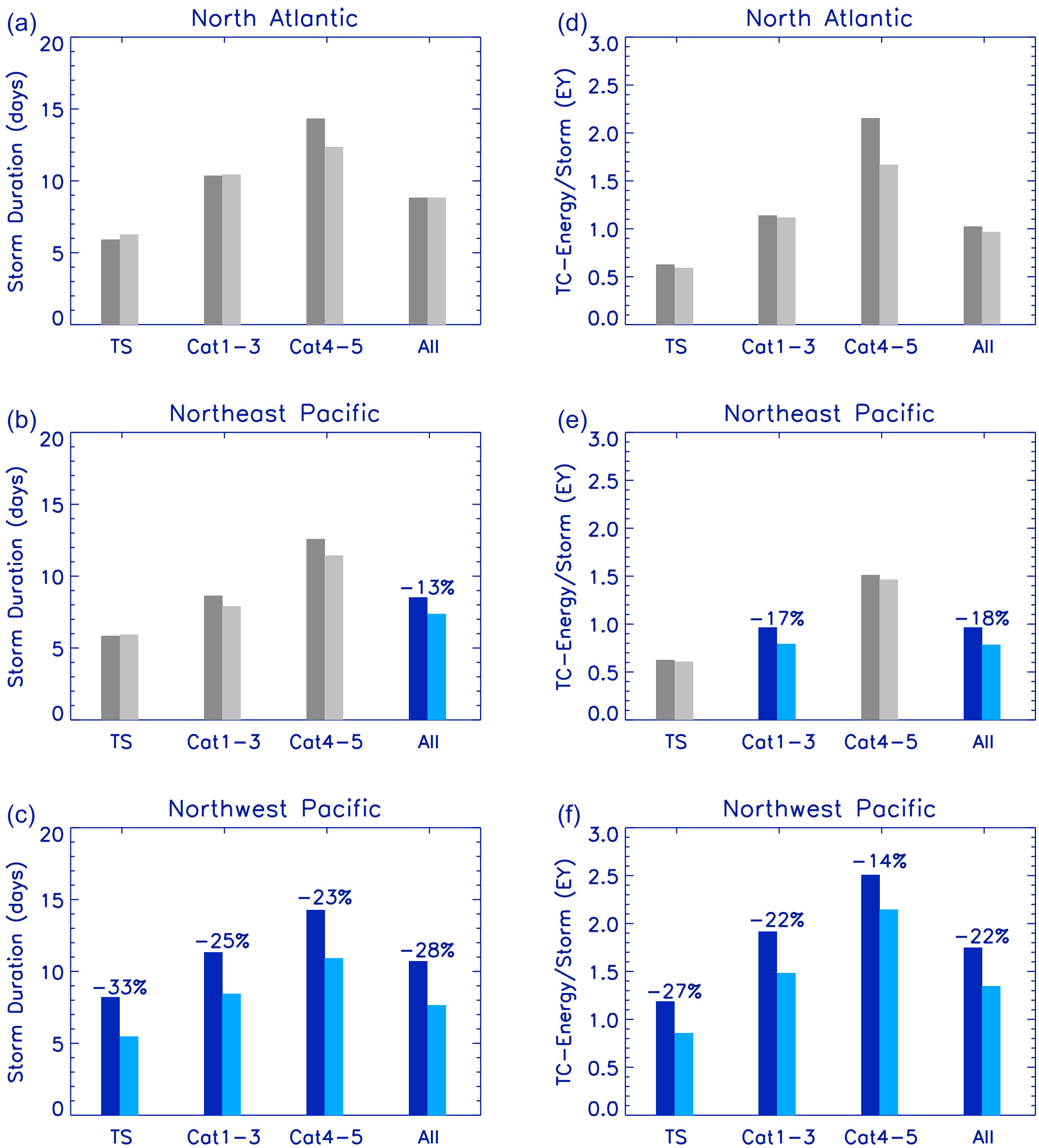

Figure 5. Same as Figure 4, except for the (a–c) mean storm duration (days) and (d–f) mean EPS (EY) for different TC categories.

the TC energy PDF may also be affected by interbasin teleconnection through adjustment in the large-scale tropical circulations to long-term climate forcing, affecting the environment for TC development [*Wu and Wang*, 2008] (see further discussion in section 5).

5. Long-Term Changes in the Large-Scale Environment

[16] It is well known that the global or basin-scale tropical cyclone activities are affected by large-scale environment such as sea surface temperature (SST), vertical wind shear, and atmospheric stability [*Gray*, 1968, 1984; *Landsea et al.*, 1998; *Shapiro and Goldenberg*, 1998; *Cheung*, 2004; *Vecchi and Soden*, 2007; *Chan*, 2009]. For individual TC, the moisture content in the atmosphere and moisture convergence are important factors affecting storm rainfall [*Jiang et al.*, 2008; *Knutson et al.*, 2010]. To examine various large-scale environmental factors that might affect TC rainfall, we compute the linear trends of parameters that are known to affect tropical cyclone formation, genesis and intensity. These include sea surface temperature (SST), vertical wind shear (magnitude of vector difference of horizontal wind

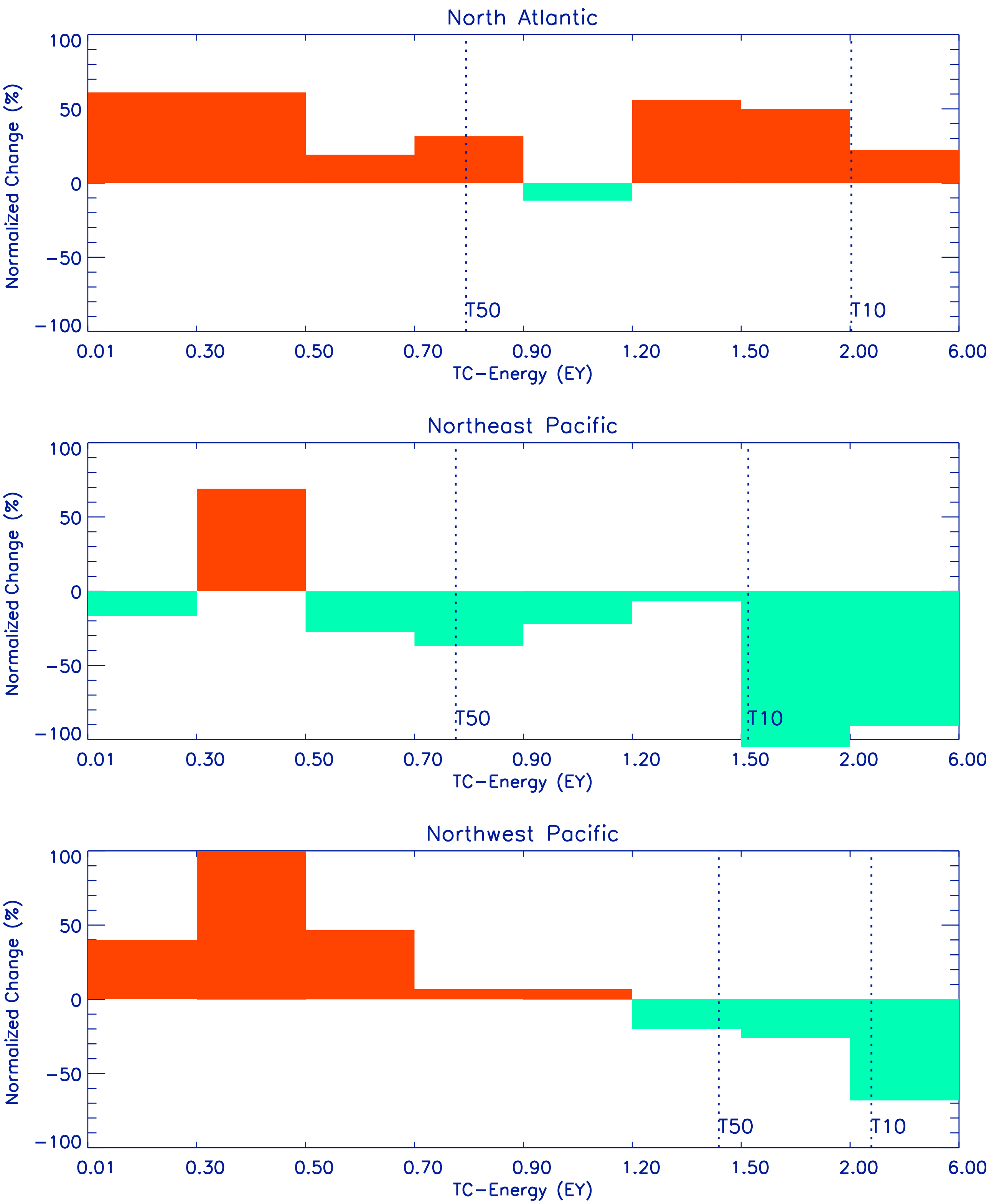

Figure 6. Normalized difference in TC frequency with EPS between the latter 10 years (1998–2007) and the earlier 10 years (1988–1997). Red indicates positive deviation, and green indicates negative deviation. The thresholds for the median (50%) and top 10% storms in EPS are marked by vertical dotted lines labeled T50 and T10, respectively.

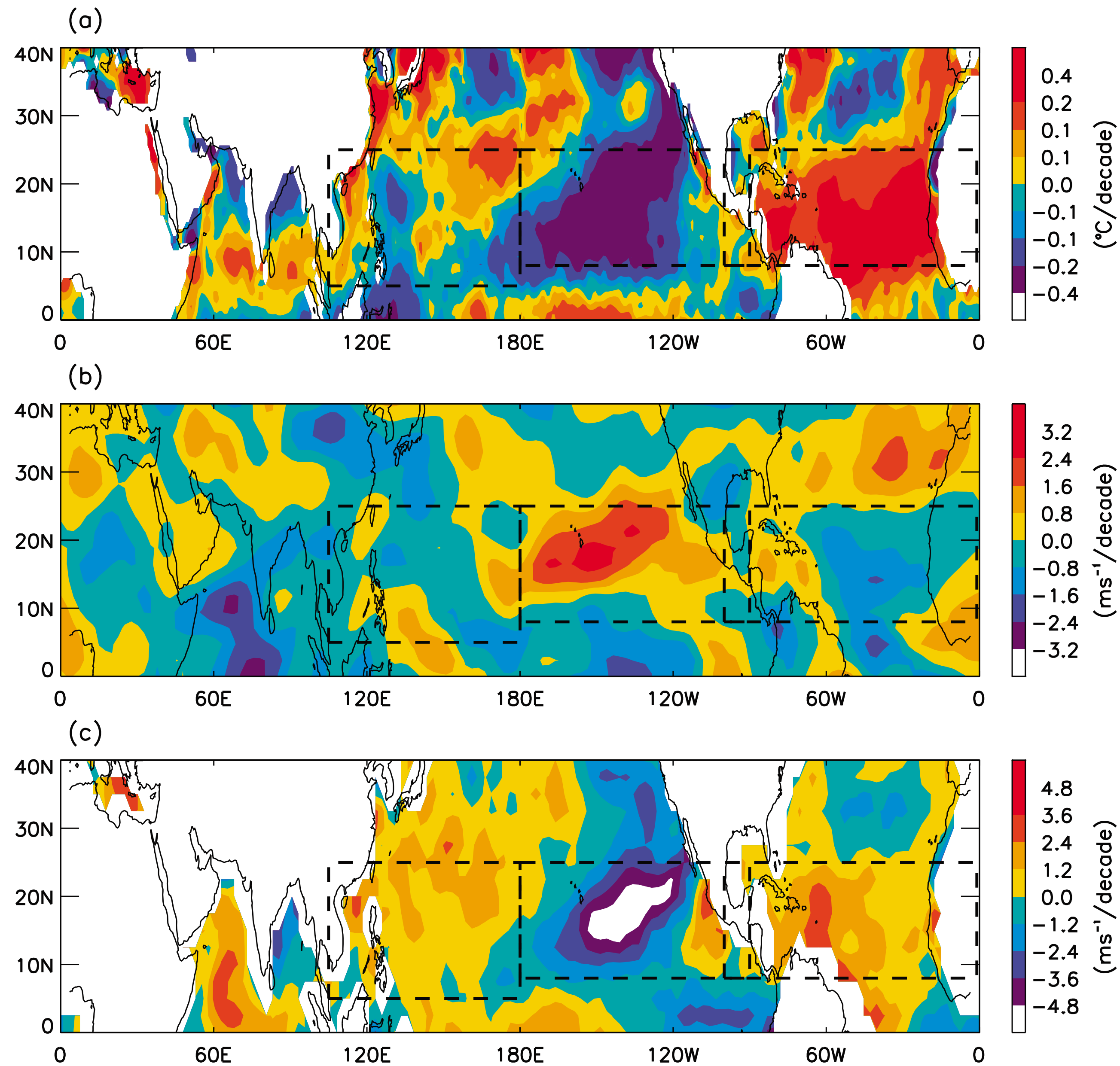

Figure 7. Linear trends of (a) relative SST, (b) vertical wind shear, and (c) relative MPI in wind in July–November from 1988 to 2007. The dotted rectangles highlight domains in each ocean basin where tropical cyclones are most likely to develop.

between 850 mb and 200 mb), the Maximum Potential Intensity (MPI) [*Emanuel*, 1986, 1995], and surface and midatmosphere relative and specific humidities. The MPI is a measure of the thermodynamic limit on the intensity of a storm based on sea surface temperature, atmospheric temperature and moisture profiles.

[17] Figure 7 shows the linear regression pattern of relative SST, wind shear, and relative MPI in velocity. We define the relative SST and relative MPI as the deviation from the zonal mean for that latitude to emphasize the interbasin differences. For unknown reasons, the midtropospheric and surface humidities do not show consistent results for the different ocean basins, and are therefore omitted from the following discussion. During the period 1988–2007, the relative SST regression pattern (Figure 7a) shows a widespread relative warming trend over the tropical North Atlantic, and an extensive region with a relative cooling trend over the northeast Pacific. The magnitude of the relative SST trend in the North Atlantic TC domain (dotted rectangle in Figure 7), including the Maximum Development Region (MDR, 10°N–20°N, 20°W–85°W) is notably the largest (>0.15°C per decade) among the tropical ocean basins. Similar magnitude in the maximum relative cooling trend (<-0.14°C per decade) is found in the northeast Pacific. The SST relative warming trends are consistent with the changes in TC rain and TC energy PDF over the two ocean basins discussed in section 4. In contrast, the northwest Pacific shows a strong negative relative SST trend over key

regions of tropical cyclogenesis east of the Philippines and in the southern and far eastern portions of the domain. The negative relative SST trend here is unfavorable for TC development and is consistent with the reduction in TC rain in the northwest Pacific.

[18] The atmospheric vertical wind shear trend pattern shows near-zonal bands of negative and positive features (Figure 7b). Negative trends appear along the equator while the positive trends appear in the margin of ITCZ, probably associated with the shift of ITCZ and Hadley circulation [*Zhou et al.*, 2011]. A large reduction of vertical wind shear, favorable for enhanced tropical cyclone activities, is found over the tropical Atlantic, particularly over the MDR. On the contrary, the northeast Pacific is dominated by increasing vertical wind shear, which suppresses tropical cyclone activities. Over the northwest Pacific, the wind shear pattern shows both positive and negative trends. The positive wind shear southeast of the Philippines near the southern part of the domain would reduce TC development there. The reduced wind shear over the key regions of tropical cyclogenesis (areas east of the Philippines and in the southeastern portion of the domain) would have favored an enhancement and shift of TC development further east. However, these are also regions of reduced relative SST, as noted in Figure 7a. It is possible that the strong negative relative SST effect overwhelms the weaker wind shear effect, thus resulting in overall reduction of TC rain in the northwest Pacific.

[19] The relative MPI patterns show a large positive relative trend over the North Atlantic and a negative relative trend over the northeast Pacific. This agrees with the changes in TC rain and related statistics in the two ocean basins. Over the northwest Pacific, the relative MPI signal is weak, and not likely to be a determining factor for the TC rain trend. As a caveat, we note that the relative MPI trends derived from the NCEP reanalysis are subject to large uncertainty because of the assimilation of inhomogeneous tropical lapse rates in the reanalyses [*Allen and Sherwood*, 2008], although some of these inhomogeneity problems may be reduced by removal of the zonal mean values. Nonetheless, caution must be exercised in using relative MPI in any interpretation of our results.

6. Summary and Discussion

[20] Using pentad GPCP data, we have estimated rainfall associated with tropical cyclones for the post-SSMI period (1988−2007) and examined the long-term trends of tropical cyclone rainfall and related statistics for the North Atlantic, northeast Pacific, and northwest Pacific. We find that during the period 1988–2007, TC number and TC rainfall in the North Atlantic have significantly increased at a rate of 29.9% and 23.8% per decade, respectively. In contrast, TC number and TC rain have decreased at a rate of 13.3% and 25.1% per decade, respectively, over the northeast Pacific. The opposite variation in TC number and TC rain between the two ocean basins is also found in intermediate (Cat 1–3) and strong (Cat 4–5) storms. These results are in agreement with previous studies [*Wang and Lee*, 2009, 2010], which found an apparent inverse relationship between TC activities between the North Atlantic and northeast Pacific. The northwest Pacific shows a decrease in TC number and TC rain for all categories with an overall reduction in TC number (−8.9% per decade) and TC rain (−20.9% per decade). Storm characteristics measured in terms of averaged duration (in days) per storm, and energy per storm remain largely unchanged for the North Atlantic and the northeast Pacific. However, for the northwest Pacific, there is a significant reduction in overall storm duration (−28%) and in energy per storm (−22%). As a caveat, these results are obtained from storm track data from the JTWC, but not corroborated by other data sources from China, Hong Kong and Tokyo. Analyses of TC energy PDFs reveal that overall TCs have become more energetic (wetter) in the North Atlantic, and less energetic (drier) in the northeast Pacific. In the northwest Pacific, we find an internal shift in the TC energy PDF, indicating an increase of less energetic TCs, and a decrease in more energetic TCs. However, it is inconclusive as to whether the mean rain rate for TC has changed in recent decades, based on our current methodology. An approach using high-resolution (3-hourly, 0.25×0.25 degree) TRMM rainfall data to define TC rain intensity in terms of maximum instantaneous rain rate is a part of an ongoing investigation.

[21] Large-scale environmental variables, specifically relative SST, vertical wind shear and relative MPI have been analyzed to shed light on the trend differences, and the shift in rainfall PDF among ocean basins. Notably, the North Atlantic has experienced in the last two decades, a large increase in relative SST and reduction in wind shear, which may explain the largest increase in TC rain. On the other hand, in the northeast Pacific, an extensive SST cooling relative to the other ocean basins, and an increase in vertical wind shear, are likely to suppress TC activities and account for the observed significant negative trend in TC rain there. Over the northwest Pacific, a negative relative SST trend over the key regions of tropical cyclogenesis may have contributed to the negative TC rain trend.

[22] Finally, we caution that, even using the state-of-the-art rainfall data set, the record length is still far too short, and the spatial and temporal resolution of the rainfall data are grossly insufficient for a definitive assessment of the long-term trend in TC rain rate. Given that long-term (multi-decadal) high-resolution oceanic rainfall data are unlikely to be available in the near future, this paper offers alternate measures of TC rain, and storm characteristics that could be used to explore the validation of model results with rainfall observations. Furthermore, the results in this work are subject to uncertainties in the satellite data as discussed in section 3. These considerations underscore the need for extending and improving long-term rainfall data to obtain reliable estimates of tropical cyclone rainfall such as planned under the Global Precipitation Measurement (GPM) program [*Hou et al.*, 2008].

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